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An assessment of wind power prospects in the Brazilian hydrothermal system

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ABSTRACT

Despite the need to reduce greenhouse gases, thermoelectric power plants were the main winners in electricity auctions held until 2009. This study evaluates the possibility of improving the prospects of increasing the clean and renewable energy mix. The new official energy plan for 2030, prepared for the Brazilian Government by the Energy Research Company (EPE[1]), forecasts a relative increase in thermal generation using natural gas, coal and nuclear energy. In contrast to this plan, this study considers wind generation as a complement to hydropower rather than fossil and nuclear energy. Previously, the analysis of seasonal complementarities in Brazil between average inflow hydraulic energy (ANAh) and average inflow wind energy (ANAw) has been generally focused on an intra-annual period. However, in this study, an initial effort is made to analyze the multiannual complementarities of the two sources. The wind technology learning curve in Brazil and worldwide was investigated, and the results show the potential of competitiveness of wind power compared with other sources, such as nuclear power, gas and coal. The replacement of thermal-based expansion by wind power was simulated by a comparative analysis of the net present value (NPV) of fuel, operation, maintenance and capital costs, including the potential learning time, of both scenarios. The NPV results indicate that the total costs of wind generation represent 57% of the total thermal costs, showing its potential attractiveness and that it facilitates the reduction of the emission of greenhouse gases. Taking into account the population and the stabilization of energy demand in the 2040s, the possibility of meeting the energy demand of Brazil through renewable and sustainable energy sources, mainly hydropower and wind power, is demonstrated.

Contents

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[1] The abbreviation in Portuguese for Empresa de Pesquisa Energética.

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Nomenclature

ANAh	Average inflow hydraulic energy
ANAw	Average inflow wind energy
ANEEL	National Agency of Electrical Energy
BIG	Power generation database
CCEE	Board of Electric Energy Commercialization
CE	Cost of energy
CF	Capacity factor
EPE	Energy Research Company
FRC	Capital recovery factor
GWEC	Global Wind Energy Council
NOAA	National Oceanic Atmospheric Administration
NPV	Net present value
ONS	National System Operator

1. Introduction and background

From 2005 to 2009, thermal power increased its relative market share compared with renewables in Brazilian electricity auctions. In the seventh new-energy auction in 2008, 60.3% of the winning bids were from thermal sources according to the Board of Electric Energy Commercialization (CCEE[2]) [1]. Renewable energy improved its share only in the last four auctions, partially because of one exclusive auction for wind power in 2009.

After harsh criticism by the environmentalists and specialists of the Brazilian electric sector, the most recent ten-year plan of EPE 2010–2019 [2] presented a deviation from the previous ten-year plans by forecasting a comeback for renewable sources. This prediction reflects the greater competitiveness of alternative sources compared with thermal sources in recent Brazilian auctions. However, the long-term, 30-year plan developed by EPE in 2007 [3] calls for 22,900 MW of thermal generation, mainly nuclear power, natural gas and coal.

The widely recognized advantages of wind power generation compared with thermal sources derive from the environmental benefits of wind power, such as the lack of emission of carbon dioxide in the atmosphere. In addition to being clean and renewable, wind power complements the hydrological regime, mainly in the Northeast Region of Brazil [4]. This region possesses high wind power potential and has been, until recently, importing energy from other parts of the country.

Currently, wind energy represents only 1.38% of the Brazilian electrical power supply according to the power generation database (BIG[3]) [5] of the National Agency of Electrical Energy (ANEEL[4]). With 1.638 MW, this contribution is limited when compared with wind-energy use in several European countries, the United States, China and India. Nevertheless, according to the World Wind Energy Report 2009 and 2010 [6], Latin America had the world's highest annual growth (113.3%) in wind energy, which is mainly attributed to the Brazilian and Mexican efforts in 2009 after years of stagnation. In 2010, the growth in Latin America was not large in absolute terms. However, it represented a 30.8% increase in capacity well above worldwide average, but much bellow the previews year. The United States is no longer the world leader in installed capacity, having lost the leadership to China in 2010. The goal of the United States is to meet 20% of its electricity demand with wind power by 2030. For this purpose, the government provides credits to stimulate new plants and component manufacturing. The Chinese government has prioritized the achievement of a sustainable energy supply based on renewable energy. In 2010, China became the market leader in installed wind capacity with 44,733 MW. World Wind Energy Association, by the end of 2010, there were 196,630 MW installed in wind farms worldwide.

The European countries have adopted various policies to develop wind energy: feed-in tariffs, tendering systems[5] and the trading of green certificates.[6] The most successful countries in the implementation of wind energy are Spain, Denmark and Germany, which have adopted the feed-in tariff scheme [7]. These countries pay less for wind energy than England, for example, which adopted an auction system [7].

In 2009, 2010 and 2011, the Brazilian government held energy auctions, some of which were dedicated to alternative energy sources. According to the CCEE, the first auction in 2009, exclusively for wind power, contracted 1805.7 MW [1] at an average price of R$ 148.39/MWh (85.81 USD/MWh)[7] from 71 wind projects in the northeast and south regions of Brazil. The second auction for alternative sources, held in August 2010 [1], achieved 2047.8 MW from 70 wind-power projects at an average price of R$ 130.86/MWh (74.47 USD/MWh)[8] in addition to biomass and limited capacity hydropower. In 2011, there were three auctions: the renewable-energy auction, A-3 and A-5. The renewable energy auction sold 34 wind-power contracts at a price of R$ 99.54/MWh (61.97 USD/MWh) and a capacity of 861.1 MW. The A-3 auction, held in August 2011 [1], sold 1067.6 MW of wind power at a price of R$ 99.58/MWh (62.91 USD/MWh). The A-5 auction sold contracts for 39 projects at R$ 105.12/MWh (56.80 USD/MWh) and a capacity of 976.5 MW (Table 1). Although favored by the exchange rate, the prices at these auctions show that wind energy is claiming its place without subsidies, particularly in northeastern and southern Brazil.

However, public policies are necessary to encourage wind energy in Brazil. Measurements and modeling are necessary at each site for the appropriate choice of wind turbines with high efficiency. Because operating and maintenance costs can be higher than forecasted, monitoring is required. In addition, because the National System Operator (ONS) has shown that the wind power operation capacity factors were lower than the values forecasted during design of the original projects and used in auctions, capacity factor forecasting methodology must be carefully reassessed. This decrease in capacity factors could be caused by optimistic production projects, the unsuitability of the generators to local wind regimes and poor wind measurements data.

In the present study, the replacement of thermal power proposed by the official EPE 30-year wind-power plan is simulated by comparing the NPVs of the investment, operation, maintenance and fuel costs of each alternative. CO_2 emission costs for the fossil option are also estimated. In addition, the learning curve for wind power in Brazil, which is based on real-world results, is examined to

[2] The abbreviation in Portuguese for Câmara de Comercialização de Energia Elétrica.

[3] The abbreviation in Portuguese for Banco de Informações da Geração.

[4] The abbreviation in Portuguese for Agência Nacional de Energia Elétrica.

[5] A fixed amount of installed capacity is announced and contracts are awarded through a competitive bidding process, which offers the winners a set of favorable conditions for investment, including grants per kW installed.

[6] Renewable energy certificates are traded in a parallel market. Their price is set according to the conditions of supply and demand. Producers benefit from the sale of these certificates.

[7] Exchange rate: R$1.7293/USD 1 in December 2009. *Source*: Brazilian Central Bank (BCB).

[8] Exchange rate: R$1.7572/USD 1 in August 2010. *Source*: Brazilian Central Bank (BCB).

Table 1
Contracted capacity and prices of wind power auctions in Brazil.
Source: EPE and CCEE (2012).

Year	Contracted capacity (MW)	Price (R$/MWh)	Price (US$/MWh)	Number of projects
2009	1805.70	148.39	85.81	71
2010	2047.80	130.86	74.47	70
2011	861.10	99.54	61.97	34
2011	1067.60	99.58	62.91	44
2011	976.50	105.12	56.80	39

estimate future investment costs. Positive results for the combination of wind power and hydropower compared with hydropower and thermal power confirm the economic advantages and environmental benefits to the country of enhancing the renewable energy mix. The complementarities between naturally affluent hydraulic and wind energy on annual and multiannual bases are assessed for northeastern Brazil.

2. Methodology

This work was conducted in five steps. Step one: the complementarity between wind and hydro resources were simulated from ten coordinates of data from NOAA [8] for wind in the Northeast of Brazil and from ONS [9] for hydro availability. This simulation enabled an estimation of the expected capacity factor for wind farms and an indication of complementarity between these two sources. The Appendix details the method used to estimate the ANAw from the average monthly wind speeds. Step two: official plans for the expansion of Brazilian power capacity have been reviewed. The total capacity and expected energy production of proposed thermal power plants such as nuclear power, coal and natural gas were reviewed. Then, for each scenario of hydro generation, the installed capacity and annual energy production by wind power in substitution of thermal generation was estimated. Step Three: the gains from learning and scale have been evaluated to assess the progress ratio and the reduction in investment cost for wind power capacity. Step Four: the thermal generation capacity identified in step 2 was replaced by wind power to provide the same amount of energy that was expected to be generated by the avoided thermal capacity in each scenario involving hydropower availability. Economic analyses were performed to calculate the NPV of each alternative by considering the investment cost, operation and maintenance costs, fuel costs and the benefit of avoiding the costs of CO_2 emissions due to wind power. Additionally, economic analyses were performed with and without learning and scale gain. Step Five: finally, the potential of supplying the total power demand in 2040, when the Brazilian population is expected to stabilize, with renewable sources, mainly wind power and hydropower, is evaluated while taking into account the doubling and tripling of per capita consumption.

3. Complementarities between natural affluent hydraulic and wind energy in northeastern Brazil

In Brazil, the analysis of the seasonal complementarities between the average inflow hydraulic energy (ANAh) and the average inflow wind energy (ANAw) has mainly focused on the intra-annual period, as a pioneering study [10] presents evidence of complementarity between seasonal water regimes, wind and the consequent stabilization of the national energy supply. However, apart from considering intra-annual complementarities, guaranteeing that supply meets demand requires an assessment of multiannual complementarities because the naturally affluent energy of both hydropower and wind sources varies over the years and because the hydropower-generating dam reservoirs are managed multiannually. The question that requires investigation is whether there is a tendency for decreased water affluence to be compensated by higher wind availability and vice versa. An initial effort is made in this investigation despite the limited availability of data. The database [8] created with the data from the United States NOAA (National Oceanic Atmospheric Administration) enables the measurement of trends illustrating the potential for intra and multiannual complementarity to be examined in detail, which requires further study. Covering the years from 1948 to 2010, the database comprises the monthly average wind speeds for ten sets of coordinates in the northeast Brazil and the monthly ANAh for northeast Brazil. The Appendix describes the method used to estimate the ANAw from the average monthly wind speeds. The use of the monthly wind speed average to estimate the ANAw constitutes an approximation.

Figs. 1–4 show the complementarities of the ANAw and ANAh in the northeast region of Brazil from 1948 to 2010 with the values normalized to unity, or per unit (p.u.), for the monthly average. The values greater than 1 represent monthly ANAh and ANAw values greater than the average, whereas the values less

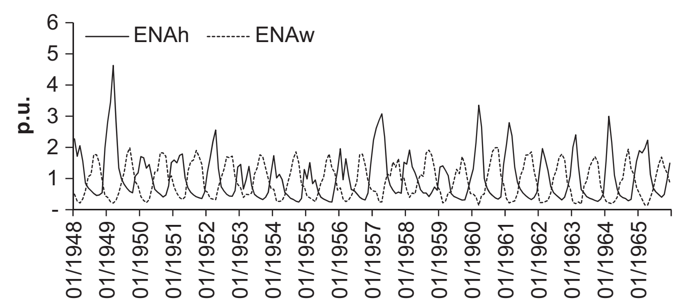

Fig. 1. Average monthly normalized (p.u.) natural affluent energy: ANAw and ANAh (1948 to 1965).

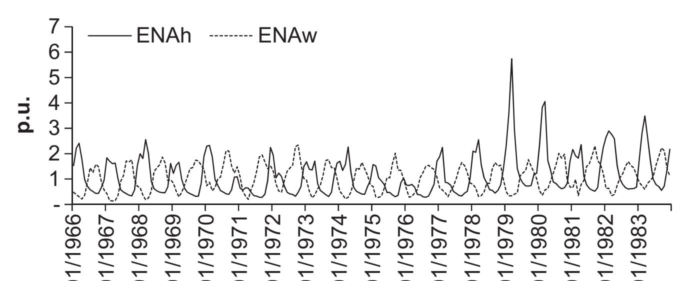

Fig. 2. Average monthly normalized (p.u.) natural affluent energy: ANAw and ANAh (1966 to 1983).

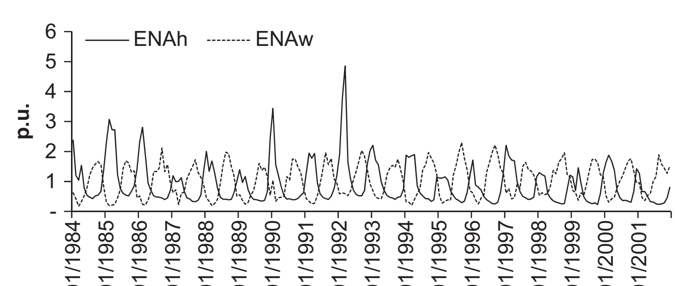

Fig. 3. Average monthly normalized (p.u.) natural affluent energy: ANAw and ANAh (1984 to 2001).

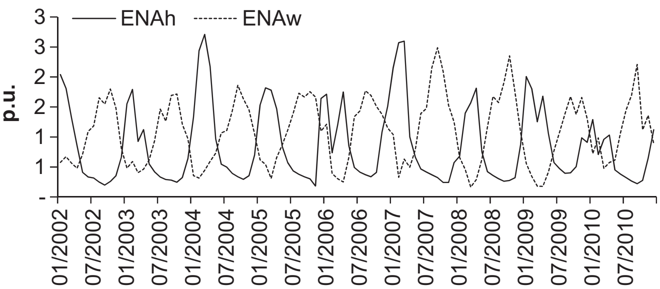

Fig. 4. Average monthly normalized (p.u.) natural affluent energy: ANAw and ANAh (2002 to 2010).

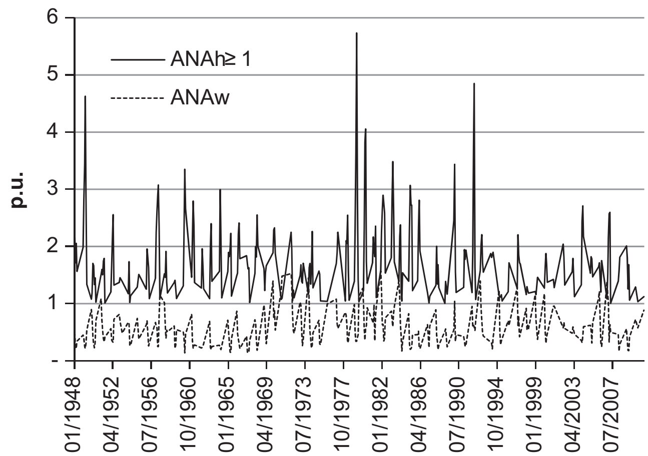

Fig. 5. Complementarity of wind power and hydropower with ANAh $\geq$ 1.

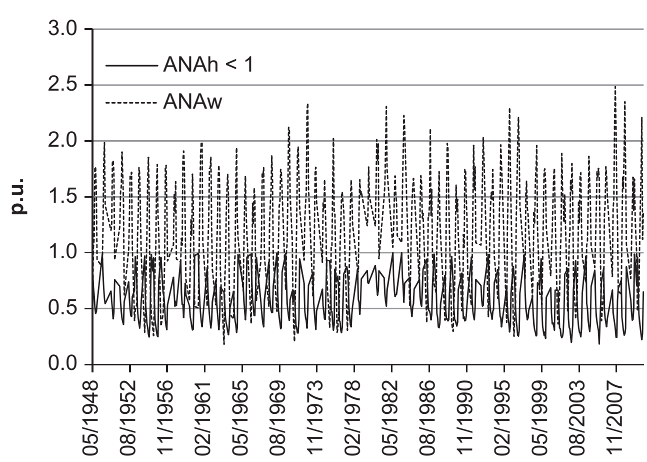

Fig. 6. Complementarity of wind power and hydropower with ANAh $<$ 1.

than 1 represent ANAh and ANAw values lower than the average. The correlation coefficient for all monthly ANAh and ANAw values from 1948 to 2010 is 0.62, indicating a strong complementarity. In all but six months (April and December, 1963: 0.83 and 0.95, respectively; March and April, 1971: 0.99 and 0.85, respectively; May 1976: 0.99; and May 2001: 0.93), the sum of ANAh and ANAw exceeds 1. This result indicates that the combined capacity factor is almost always likely to exceed 50% in the implementation of a power capacity composed of equal shares of wind power and hydropower with the characteristics depicted in this database.

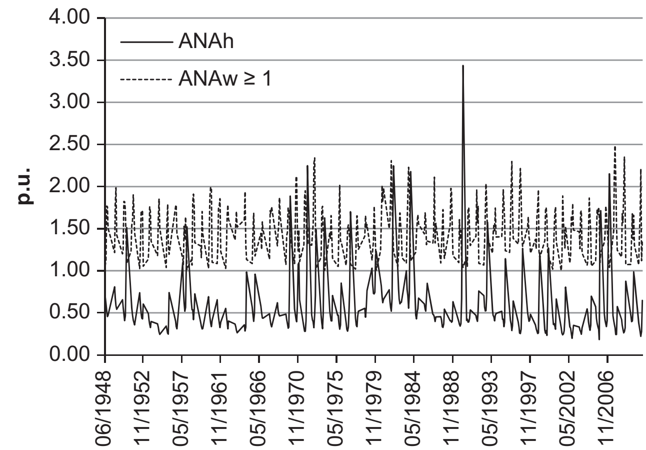

Fig. 7. Complementarity of wind power and hydropower with ANAw $\geq$ 1.

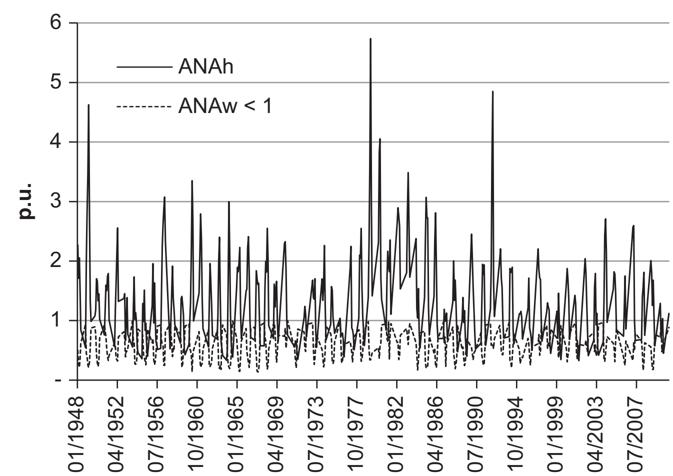

Fig. 8. Complementarity of wind power and hydropower with ANAw $<$ 1.

The ANAw series for the period 1948–2010 enabled an estimation of the expected capacity factor for wind farms at 40.2%. However, recent data released by ONS [24] shows that the capacity factor achieved by wind power in operation in Brazil was less than this estimated value. On average, the capacity factor has been 34% in northeast Brazil according to ONS (2012). Therefore, in this work, both capacity factors were considered in the simulations.

Examining a few specific cases is valuable to reinforce the trend in complementarities.

(a) Values for the ANAw when the ANAh is equal or above average: Fig. 5 shows that, for 89.4% of these 282 months, the ANAw is equal to or below average;
(b) Values for the ANAw when the ANAh is equal to or below average: Fig. 6 shows that, for 70.5% of these 474 months, the ANAw is equal to or above average;
(c) Values for the ANAh when the ANAw is equal to or above average: Fig. 7 shows that, for 91.8% of these 364 months, the ANAh is equal to or below average;
(d) Values for the ANAh when the ANAw is equal to or below average: Fig. 8 shows that, for 64.3% of these 392 months, the ANAw is equal to or above average.
(e) Out of 756 months, only in 30, ANAw and ANAh, both simultaneously, were above average (1.0) and in 140 months both were simultaneously below average.

Table 2
Assumptions and data for thermal sources: costs and the capacity factor.
Source: ONS [9], CCEE [1], EPE [3], personal information, Diuana [11], Carvalho and Sauer [18].

Thermal plant	Investment cost (USD/kW)	O&M cost (USD/MWh)	Fuel cost (USD/MWh)	Capacity factor (Average hydrology) (%)
Nuclear	5800	15	10.4	87
Coal	2150	8	15.79	45
Natural gas combined cycle	1000	3 (fixed cost)&5(variable cost)	51.18	50
Natural gas open cycle	600	3 (fixed cost)&5(variable cost)	71.09	50

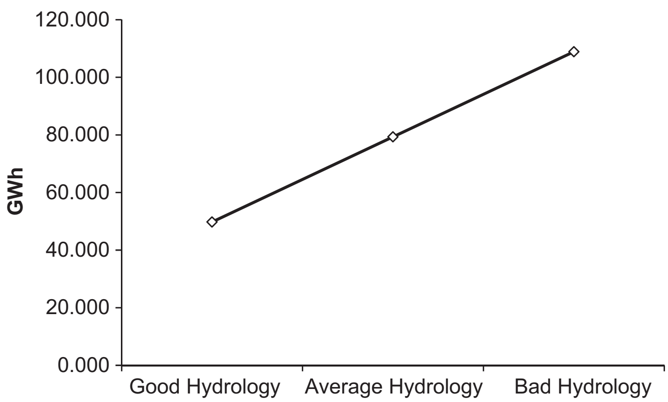

Fig. 9. Thermal generation in the three hydrology scenarios.

Table 3
Capacity factor sensitivities.

Capacity factor	Natural gas (%)	Coal (%)	Nuclear (%)
Good hydrology	10	40	87
Average hydrology	50	45	87
Bad hydrology	90	50	87

3.1. EPE plan and thermal power costs

The total new thermal capacity in the EPE 30-year plan is 22,900 MW. This study considers only 15,500 MW (51.6% natural gas, 25.8% nuclear and 22.6% coal), and this amount is replaced with wind power capacity. Only this amount was expected to be available after the year 2015, and the remaining capacity was assumed to be contracted already. The assumptions and data for investment, operating and maintenance costs, fuel costs and the capacity factor for thermal power plants are presented in Table 2. The capacity factor is the ratio of the effective production of a plant during a given time period to the maximum capacity of the plant for the same period. Three hydrology scenarios were adopted. The first scenario possesses good hydrology, which means that the capacity factor is high for hydraulics and low for thermals. In the second scenario, the hydraulics operates with the average capacity factor. In the third scenario, the hydraulic capacity factor is low, and the thermal capacity factor is high. In Table 2, the capacity factor used represents average hydrology, which is, by definition, the expected performance on the long range. Bad and good hydrology may only prevail for short periods. When complementary wind availability is not high enough to compensate fully for bad hydrology, reserve thermal power may be required. The plant lifetime was assumed to be 30 years, and the reference discount rate was assumed to be 8% a.a.

All costs were calculated until 2030 and then discounted to the 2011 present value with a net discount rate of 8%. The total cost for thermal power plants in 2011 in an average hydrology scenario is approximately 31.2 billion USD, where the dispatch is on average with a capacity factor of 50% (adopted in this work) for a natural-gas thermal plant, 45% (adopted in this work) for a coal thermal plant and 87% for a nuclear thermal plant. The capacity factor of 87% is common in the nuclear sector. A nuclear plant usually operates on a base load.

3.1.1. Sensitivity analyses

The thermal generation until 2030 in the three hydrology scenarios is provided in Fig. 9 with the capacity factors in accordance with Table 3 because the thermal capacity is always 15,500 MW.

Fig. 10 shows the sensitivity analyses of the NPV of thermal generation costs as a function of discount rate, hydrology performance and natural gas costs. A medium NPV of 31.2 million USD is the result of a discount rate of 8%, average hydrology and a natural gas cost of 7.5 USD/MMBTU.

The results for discount rates of 6% and 10%, good and bad hydrologies and natural gas rates of 5 USD/MMBTU and 10 USD/MMBTU are also depicted.

These values are shown in Fig. 10, which is a sensitivity analysis of the thermal plants.

3.2. Replacing thermal power plants with wind power and wind power costs

To provide the same amount of energy generated with 15,500 MW of thermal power in the average hydrology scenario, 22,638 MW (Fig. 1) of wind-power capacity with an annual capacity factor of 40% will be required (see Section 2). This forecast represents the same degree of risk that EPE forecasts, with a 5% risk of noncompliance.

The database of investment costs was taken from the 2006 Proinfa Program and the auctions of 2009, 2010 and 2011. For 2011, a weighted average of the auctions with their respective capacities was calculated because there were three wind-energy auctions that year (Table 4). The figure of merit (R$/MWh—total generation cost) was converted back into a capacity investment cost in USD/MWh (Table 5).

Based on the auction data and Proinfa energy costs, US$/MWh, the capital investment costs of wind technology, to allow comparison with the usually available figure of merit in US$/kW, can be estimated using the following formulas:

$$\mathrm{CE} = \frac{I_0 \times 1.05 \times \mathrm{FRC}}{1\ \mathrm{kW} \times 8760h \times \mathrm{FC}} \tag{1}$$

$$\mathrm{FRC} = \frac{i(1+i)^n}{i(1+i)^n - 1} \tag{2}$$

where CE is the cost of energy (USD/MWh); I_0 is the investment cost (USD/kW); FRC is the capital-recovery factor; FC is the capacity factor; 5% is the percentage amount (based on I_0) estimated to represent operation and maintenance cost.

The operation and maintenance costs were assumed, as presented in Table 2. The assumed costs consider spending over a 30-year period, which is the life cycle of a plant. The cost to implement

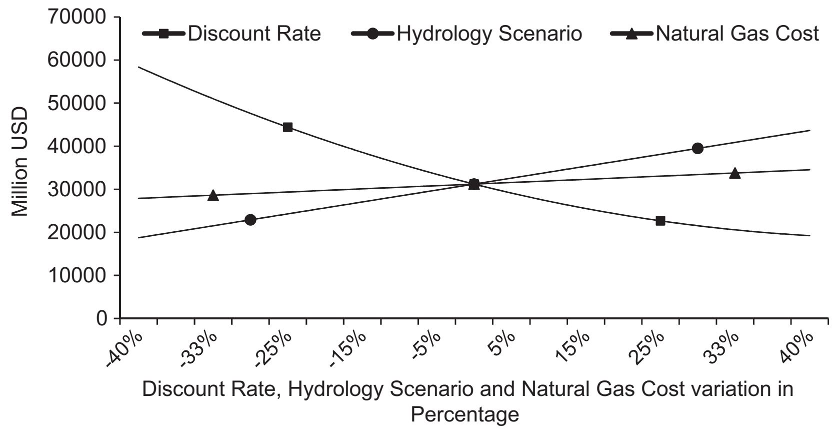

Fig. 10. Sensitivity curve: the present value of thermal plants.

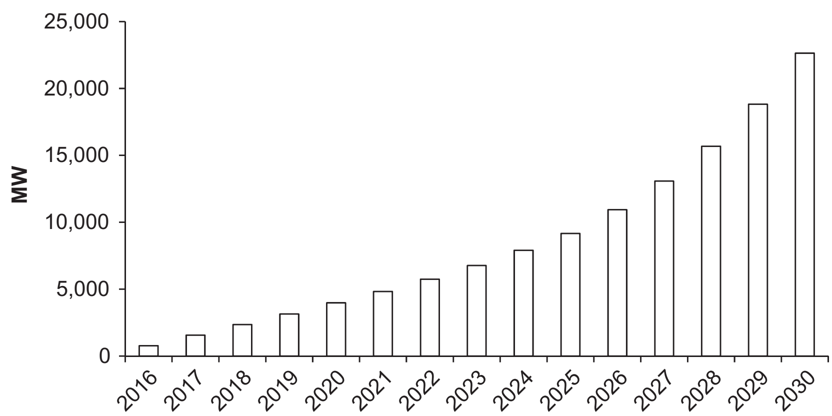

Fig. 11. Wind capacity for thermal substitution.

Table 4
Database for wind sources: costs and contracted capacity.
Source: Brazilian Central Bank (BCB).

Year	Program/Auction	Cost (USD/MWh)	Total contracted capacity (MW)
2006	Proinfa	95.61	1452
2009	Auction	85.81	3449
2010	Auction	74.47	5053
2011	Auction	60.58	8424

Exchange rate: R$2.3407/USD 1 in January 2006. Source: Brazilian Central Bank (BCB). Exchange rate: R$1.7293/USD 1 in December 2009. Source: Brazilian Central Bank (BCB). Exchange rate: R$1.7572/USD 1 in August 2010. Source: Brazilian Central Bank (BCB). Exchange rate: R$1.5830/USD 1 on August 17th, 2011; R$1.6062/USD 1 on August 18th, 2011; and R$1.8508/USD 1 on December 20th, 2011.

Table 5
Conversion of the figure of merit into the capacity-investment cost.

	2006	**2009**	**2010**	**2011**
Cost of generation (USD/MWh)	95.61	85.81	74.47	60.58
Investment cost (USD/kW)	3191	2864	2485	2022

22,638 MW by 2030 is brought to a present value with a discount rate of 8% per year, and the total cost in present value for the wind-power supply is approximately 17.8 billion USD, excluding the learning gain, which is lower than the total cost of the thermal plants.

In contrast, the investment cost of wind-power technology is higher than the investment cost of thermal power plants, as shown in Table 6. However, although wind-power plants produce operation and maintenance costs, which are lower than those of the thermal power technologies, the plants have no fuel cost and no costs related to CO_2 emissions. Under these conditions, the total cost of thermal power is greater than the total cost of wind power, as shown in Table 6.

“Contracted capacity” refers to what was contracted in each year for wind power but not necessarily for commercial operations.

Hydraulic and wind power would be complemented by natural gas thermal plants when the hydrology scenario is critical.

3.3. The wind-power learning curve and the estimation of future costs

The learning curve for wind-power plants represents the cost reduction with economies of scale and learning. According to Junginger et al. [12], “The Progress Ratio (PR) is the parameter that expresses the rate at which costs decline each time the cumulative production doubles”. A PR of 90% equals a learning rate of 10%, representing a decrease of 10% in costs for each doubling of capacity.

According to Neij [13], the learning curve can be expressed as follows:

$$C_{\mathrm{cum}} = C_0 \times C_{\mathrm{um}}^{b} \tag{3}$$

Table 6
Costs in present value of thermal power plants and wind power with and without learning gain for average hydrology at a discount rate of 8% and a natural-gas cost of 7.5 USD/MMBTU.

Present value (Million dollars)	Investment	O&M	Fuel	Emission of CO_2	O&M+20 years	Fuel+20 years	Emissions+20 years	Total
Thermal plants	13,808	1797	4135	1135	2341	6251	1734	31,201
Wind power	16,030	726	–	–	976	–	–	17,732
Wind power PR 85%	15,230	726	–	–	976	–	–	16,932
Wind power PR 83%	14,380	726	–	–	976	–	–	16,082
Wind power PR 77%	11,347	726	–	–	976	–	–	13,049

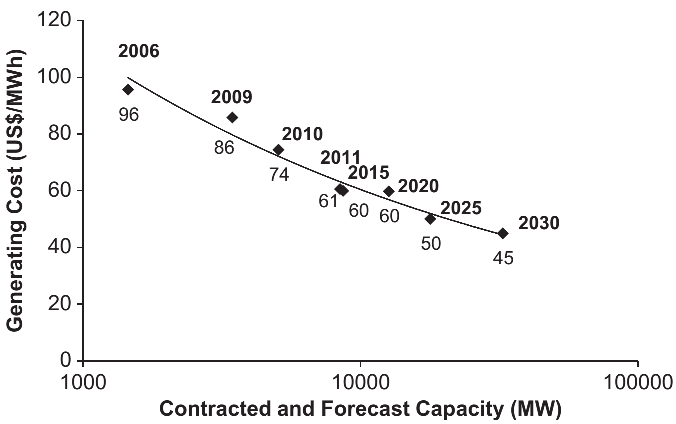

Fig. 12. Forecast of the investment cost for wind power based on a learning curve with a PR of 83%.

$$\mathrm{Log}(C_{\mathrm{cum}}) = \mathrm{Log}(C_0) + b \times \mathrm{Log}(C_{\mathrm{um}}) \tag{4}$$

$$\mathrm{PR} = 2^b \tag{5}$$

$$\mathrm{LR} = 1 - 2^b \tag{6}$$

where C_{cum} is the cost per unit; C_0 is the cost of the first unit produced; C_{um} is the accumulated production (in units); b is the index of experience; PR is the progress ratio; LR is the learning rate.

Junginger et al. [12] has studied the global learning curve, considering cost in Spain and the United Kingdom and the global installed capacity. He states that the learning curve for the UK represents a progress ratio of 81%, which is associated with a learning rate of 19%. For the Spanish case, he has shown a PR of 82% in the first phase and a PR of 85% in the second phase, demonstrating that the learning gain was higher in the first phase (Fig. 11).

The learning and experience curves predict an increase in the competitiveness of wind power, a novel industry in Brazil. To develop the Brazilian learning curve, recent experience and the data on wind-power capacity contracted by the Incentive Program for Alternative Energy Sources (PROINFA)[9] [14] and the 2009, 2010 and 2011 wind-power auctions with their corresponding costs have been reviewed. The data are presented in Fig. 12. A progress ratio of 83% was obtained, which is compatible with the international performance median learning gain described by Junginger.

In the Brazilian learning curve, there are only four key data points. The first point, from PROINFA, differs in nature from the other points because it resulted from a different type of auction. The contracts were not awarded based on technical and economic merit, but on the antiquity of the environmental license, as determined by legislation enacted in 2002, under influence from the holders of the environmental licenses. Therefore, there was no market competition. The last three auctions (2009, 2010 and 2011) were based on economic competition. However, the auctions were also influenced by the decline in the exchange rate because most equipment is imported. According to Blanco [15], the experience curve is a means to predict long-term cost trends. "The experience curve is not a forecasting tool based on estimated relationships; it merely notes that, if the existing trends continue in the future, then we may see the proposed decrease." Thus, according to the learning curve, it is possible to estimate the wind-power costs for the EPE 2030 plan. According to the expected performance, the cost of energy in 2030 with an 83% PR, i.e., a 17% reduction in the cost of the technology for each doubling of capacity, would become 45 USD/MWh.

These data were based on Proinfa in 2006 and the three auctions (2009, 2010 and a weighted average of the 2011 auctions). Then, the amount by which the cost would decrease each time the contracted capacity doubled was calculated. In the first four points, there was a PR of 83%, and the PR was assumed to remain the same until 2030. Thus, each time the capacity contracted doubles, the cost generation decreased by 17%.

Junginger et al. [12] suggests using a PR range of 77% to 85%, with an average of 81%. In this study, a progress ratio of 83% has been determined, which is close to the median suggested value, and thus this ratio will be adopted with the extreme values of 77% and 85%. With a PR of 77%, the cost of wind energy by 2030 will decrease to 35 USD/MWh, and with a PR of 85%, the cost will decrease to USD 50/MWh. Considering the learning-curve values, the investment cost of wind power with a PR of 77% will be approximately 11.3 billion dollars. This result indicates the investment cost of wind power becomes more economical than the investment cost of thermal power at this learning rate.

For learning gains with PRs of 83% and 85%, the wind-power investment cost is higher than that of thermal power. However, wind power does not entail a fuel cost, and for this reason, wind power becomes more attractive.

With a capacity factor of 32% (Fig. 14), the investment cost of wind power with a PR of 77% is higher than the thermal power cost, but the total cost is always less than that of the thermal power plants.

Given a capacity factor of 40% for wind power, the total costs are represented in Table 6.

As shown in Table 6, the total cost for thermal power considering all costs is higher than the wind-power costs even without any learning gain. In contrast, the investment cost of wind power is lower than that of thermal plants only when the wind-power learning gain PR is 77% (Fig. 13). The thermal plants have higher costs in terms of operation and maintenance. Wind-power plants do not have fuel and CO2 emission costs.

Tables 7 to 12 show the variation of thermal plant costs and wind power plant costs with and without learning gain for all

[9] The abbreviation in Portuguese for Programa de Incentivo as Fontes alternativas de Energia Elétrica.

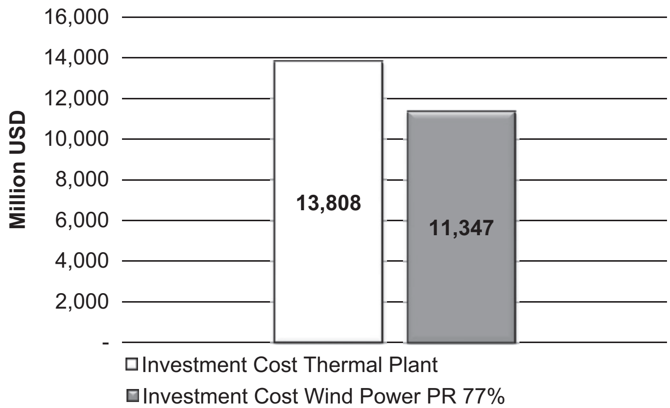

Fig. 13. Present value of the investment cost of thermal power and wind power with a learning gain of 77%.

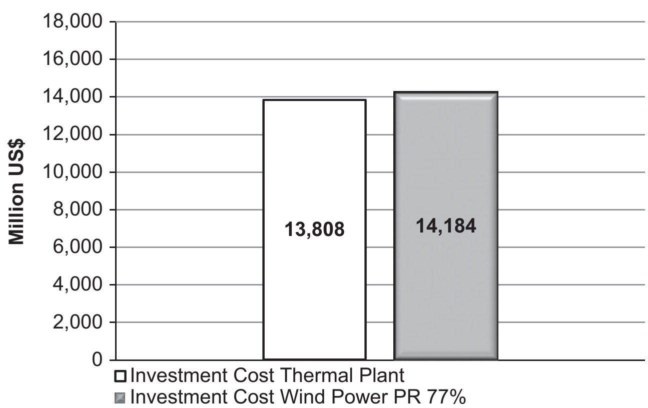

Fig. 14. NPV of the investment cost of thermal power and wind Power with a learning gain of 77% and a CF of 32%.

scenarios of hydrology, variations on discount rates and also variations in natural gas costs. Studies performed by the Brazilian Association of Wind Power (ABEEolica[10]) [16] show that, although the investment cost of wind power is higher than that of traditional thermal power, the benefits for consumers reduce the difference in investment. The efficient use of the system reservoirs and the lack of a need for fossil fuel decrease the operation cost.

According to Kouvaritakis et al. [17], for the period 1975–1993, nuclear power plants had a PR of 95%, based on the installed capacity of the countries belonging to the Organization for Economic Cooperation and Development (OECD). According to Sauer and Carvalho [18], the nuclear learning curve could be negative because the costs of building materials, labor and waste disposal as well as the need for additional security are increasing. Nevertheless, according to Kouvaritakis et al. [17], for the period of 1975–1993, coal power plants had a PR of 90%, also based on the installed capacity of the OECD countries. According to Colpier and Cornland [19], the learning curve for natural gas thermal plants shows a PR higher than 100% until 1991, which indicates an increase in prices. After 1991, the curve decreases sharply with a PR of 75%. According to MacGregor et al. [20], the main mechanical component in wind-power generation is the turbine, which has a PR of 90%. Therefore, the PR in the phase of stabilization would be 90%.

[10] The abbreviation in Portuguese for Associação Brasileira de Energia Eólica.

According to the papers cited above, the thermal plant technology has already completed its learning curve, and the trend is one of stabilization. Wind power presents favorable signs of a continuing reduction in investment cost.

To exploit the learning gains, an appropriate strategy is required. This strategy assumes that it is necessary to hire a supply package, including the gradual nationalization of the associated production chain, instead of hiring only units of wind generation.

Auctions should be conducted to expand the capacity for periods of 3 to 5 years, with two suppliers contracted simultaneously, each of whom supplies a portion of the capacity (e.g., half). Based on the amount of expanded capacity every 3 or 5 years, the first partial contract will be awarded to the supplier who provides the best price and the lowest present-value cost of installed capacity. This award may include the maintenance and operation costs and the funds required to nationalize the manufacture of components. The second fraction of the amount to be installed will be destined for second place.

Using at least two suppliers prevents the provision of electricity from becoming dependent upon a single supplier. In extreme conditions, there may be only one supplier.

For example, for the capacity to be added between 2015 and 2019, an auction could be held 4 years in advance. The supplier would then have the time to construct facilities and begin operations while diluting the cost of a sudden ramp up following the contract award. This auction could be divided into two blocks, each producing a consortium supplier.

The plants that come online later will benefit more from learning gains. However, the cost of wind power is tied to the capacity factor. Therefore, the government should perform a thorough inventory of the location and maximum efficiency of wind-power sites, establishing where the wind farms should be located for each block. It can be assumed that the best sites will be developed first.

4. The combined potential of hydropower and wind power to meet long-term demand in Brazil

According to the 2008 revision of the Brazilian population projection for 2050 performed by the Brazilian Institute of Geography and Statistics (IBGE[11]) [21], the population of Brazil will peak at 219 million people in 2040, after which time, the population will begin to decline, i.e., the number of deaths will become greater than the number of births. The present study assumes that the Brazilian population growth will stabilize in 2040 at 219 million inhabitants, as shown in Fig. 15.

According to CEPEL [22], the potential of wind power in Brazil was 143.5 GW in 2001 with wind towers of 50 m, but today, EPE estimates approximately 300 GW with wind towers of 100 m in height Despite holding excellent prospects in Brazil, offshore wind potential has yet to be evaluated. According to Eletrobras [23], the potential of hydroelectric power in Brazil is 243.6 GW. If an annual capacity factor of 40% for wind power and 50% for hydropower is assumed, these two sources combined could meet the demand of the Brazilian electrical system. Thermal plants would be needed only for backup. Table 13 shows the hydropower and wind power generation according to each capacity installed.

Today, Brazilian consumption is approximately 2.5 MWh per capita per year. Assumptions can be made to estimate the

[11] The abbreviation in Portuguese for Intituto Brasileiro de Energia e Estatística.

Table 7
Costs in present value of thermal power plants and wind power with and without learning gain for average hydrology at a discount rate of 6% and a natural gas cost of 7.5 USD/MMBTU.

Present value (Million dollars)	Investment	O&M	Fuel	Emission of CO_2	O&M + 20 years	Fuel + 20 years	Emissions + 20 years	Total
Thermal plants	17,470	2339	5416	1490	4004	10,719	2974	44,412
Wind power	20,458	947	–	–	1670	–	–	23,075
Wind power PR 85%	19,382	947	–	–	1670	–	–	21,999
Wind power PR 83%	18,205	947	–	–	1670	–	–	20,822
Wind power PR 77%	14,425	947	–	–	1670	–	–	17,042

Table 8
Costs in present value of thermal plants and wind power with and without learning gain for average hydrology at a discount rate of 10% and a natural gas cost of 7.5 USD/MMBTU.

Present value (Million dollars)	Investment	O&M	Fuel	Emission of CO_2	O&M + 20 years	Fuel + 20 years	Emissions + 20 years	Total
Thermal plants	11,041	1395	3189	873	1405	3742	1038	22,683
Wind power	12,708	563	–	–	585	–	–	13,856
Wind power PR 85%	12,106	563	–	–	585	–	–	13,254
Wind power PR 83%	11,491	563	–	–	585	–	–	12,639
Wind power PR 77%	9029	563	–	–	585	–	–	10,177

Table 9
Costs in present value of thermal plants and wind power with and without learning gain for good hydrology at a discount rate of 8% and a natural gas cost of 7.5 USD/MMBTU.

Present value (Million dollars)	Investment	O&M	Fuel	Emission of CO_2	O&M + 20 years	Fuel + 20 years	Emissions + 20 years	Total
Thermal plants	13,808	1563	1752	604	1962	2340	876	22,905
Wind power	16,030	456	–	–	613	–	–	17,099
Wind power PR 85%	15,230	456	–	–	613	–	–	16,299
Wind power PR 83%	14,380	456	–	–	613	–	–	15,449
Wind power PR 77%	11,347	456	–	–	613	–	–	12,416

Table 10
Costs in present value of thermal plants and wind power with and without learning gain for bad hydrology at a discount rate of 8% and a natural gas cost of 7.5 USD/MMBTU.

Present value (Million dollars)	Investment	O&M	Fuel	Emission of CO_2	O&M + 20years	Fuel + 20 years	Emissions + 20 years	Total
Thermal plants	13.808	2031	6517	1665	2721	10.162	2592	39.496
Wind power	16.030	730			1.342			18.102
Wind power PR 85%	15.230	730			1.342			17.302
Wind power PR 83%	14.380	730			1.342			16.452
Wind power PR 77%	11.347	730			1.342			13.419

Table 11
Costs in present value of thermal plants and wind power with and without learning gain for average hydrology at a discount rate of 8% and a natural gas cost of 5 USD/MMBTU.

Present value (Million dollars)	Investment	O&M	Fuel	Emission of CO_2	O&M + 20 years	Fuel + 20 years	Emissions + 20 years	Total
Thermal plants	13,808	1797	3160	1135	2341	4,646	1734	28,621
Wind power	16,030	726	–	–	976	–	–	17,732
Wind power PR 85%	15,230	726	–	–	976	–	–	16,932
Wind power PR 83%	14,380	726	–	–	976	–	–	16,082
Wind power PR 77%	11,347	726	–	–	976	–	–	13,049

Table 12
Costs in present value of thermal plants and wind power with and without learning gain for average hydrology at a discount rate of 8% and a natural gas cost of 10 USD/MMBTU.

Present value (Million dollars)	Investment	O&M	Fuel	Emission of CO_2	O&M + 20 years	Fuel + 20 years	Emissions + 20 years	Total
Thermal plants	13,808	1797	5110	1135	2341	7855	1734	33,780
Wind power	16,030	726	–	–	976	–	–	17,732
Wind power PR 85%	15,230	726	–	–	976	–	–	16,932
Wind power PR 83%	14,380	726	–	–	976	–	–	16,082
Wind power PR 77%	11,347	72	–	–	976	–	–	13,049

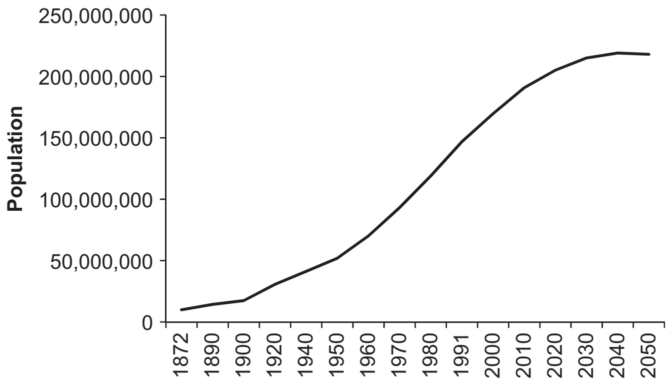

Fig. 15. Brazilian population growth until 2050.
Source: IBGE.

Table 13
Potential generation of hydropower and wind power.

Capacity (hydro and wind power)	Hydro offer (MWh)	Wind offer (MWh)	Total offer (MWh)
243.6 GW and 143.5 GW	1,066,968,000	502,824,000	1,569,792,000
243.6 GW and 300 GW	1,066,968,000	1,051,200,000	2,118,168,000

Table 14
Demand forecast for 2040 for three scenarios: 2.5, 5 and 7.5 MWh per capita.

MWh per capita	Demand forecast MWh (year 2040)
2.5	547,500,000
5	1,095,000,000
7.5	1,642,500,000

demand for 2040 using current consumption standards in Japan (6.7 MWh) and Europe (6.0 MWh), with variations among Spain, Italy, Germany, France, United Kingdom, Portugal and Ireland, ranging between 5 and 7 MWh, as a reference. Thus, two scenarios may be envisioned: a) per capita demand doubling to 5 MWh and b) per capita tripling to 7.5 MWh. (Table 14) shows the estimated demands under such assumptions.

Even if demand grows to 7.5 MWh per capita in 2040, the total offer of hydropower and wind power would meet the demand, and there would be a surplus of 475,668 GWh. Of course, these estimates are approximate, with the purpose to show the potential of existing renewable resources to meet demand. It is not expected that demand will triple, except in the case of scenario of strong penetration of electric powered vehicles to replace internal combustion engine vehicles. Neither, that all available potential resources may be developed, especially due to environmental and social issues. These questions deserve further research.

5. Final remarks and conclusions

The assessments carried out in this work indicate that enhancing the wind power mix in Brazil should be further investigated and evaluated as a source of competitively priced electricity and should be included in the government́s energy plan priorities. If the contracting strategy proposed here is followed, learning gains of wind power will be enhanced, thus increasing its economic attractiveness to the electricity sector. Furthermore, there is a potential for complementarity between wind power and hydropower, both, annually and multi-annually. This work shows also that it would be preferable to meet the demand for energy only with renewable sources, and at competitive prices, instead of thermal power sources, such as nuclear power, which has the highest investment cost and bears the risks of accidents, as occurred at the Fukushima nuclear power plant in March 2011.

However, the warning from ONS that the wind power plant capacity factor was lower than forecasted, requires prompt public policy measures to improve gathering and certification of wind data, as well as power generation capacity and availability factor for each project. Similar measures are required to monitor and estimate operating and maintenance costs over lifetime of projects.

In addition, the exchange rate in Brazil has been fluctuating recently from about 1.7R$:US$ to 2.1R$:US$. Since a significant portion of the investment depends on imported components, as the local currency depreciates, the energy costs increase, thus reducing the competitiveness of wind power. A remedy could come from increasing sharply domestic participation in the supply chain of wind industry, which could be obtained with the package contracting strategy proposed in this work.

This study analyzed wind power as a substitute for thermal power. In future research, alternative energy sources such as small hydropower, offshore wind, photovoltaic cells and cogeneration with biomass and natural gas should be assessed in addition to wind power. To accurately determine the potential for wind power in Brazil and to update the atlas of wind power, further study and measurement programs are required. The atlas was created a decade ago and did not cover fully the whole national territory. Today, with taller towers and better technology, the potential of wind power may be greater than previously assumed. If this potential is verified, further study of wind power is validated, as is the prospect for integrating wind power in the energy mix. Additionally, one can verify whether a given quantity of installed wind power can generate energy with different capacity factors, i.e., whether wind power can be fully complementary to hydro in order to meet the demand for electrical power in scenarios of good and bad hydrology if existing thermal capacity is sufficient as reserve power. Further assessment of combined hydropower and wind potential should be conducted, as well as power demand scenarios, to confirm the Brazilian potential to supply almost all demand with renewable energy. Recently several large hydropower projects have been confronted by environmental and social conflicts and controversies, mainly due to poor licensing process. Hydro plants with accumulation reservoirs are beneficial to optimize integration with intermittent sources like wind, but almost all new capacity has been run of the river, due to environmental considerations. A nationwide program to fully assess technical, economic, environmental and social feasibility of hydro, wind, solar, biomass and cogeneration resources should be implemented by the Government, in order to develop a portfolio of expansion projects that could be ordered based on these attributes.

The capability to produce wind-power generating equipment and components, such as turbines, blades and towers in Brazil, both, for the domestic demand and export, the suppliers should be further evaluated and affirmative incentive policies to support wind power production chain should be implemented to enhance the potential learning and scale gains.

Acknowledgement

The authors are grateful to Dr. Leontina M. V. G. Pinto for her insights and contribution.

Appendix A. The estimation of the ANAw

Based on NOAA data for the monthly average wind speed at ten sets of coordinates in the Northeast region of Brazil, for the period 1948–2010, and the ANAh of the Northeast of Brazil, complementarity trends were evaluated, as shown in Fig. 16. Wind data were provided by Pinto [8], and processed from NCEP Reanalysis Derived data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/; with dataset source: Kalnay et al., The NCEP/NCAR 40-year reanalysis project, Bull. Am. Meteor. Soc., 77, 437–470, 1996 (Table A1).

A larger number of wind database coordinates with hourly or shorter periods and a representative ANAh of SIN would be preferable. However, for the wind and its importance with respect to the similarity of the hydraulic ENA of the northeast region of Brazil as well as the southeast, central and northern regions of Brazil, the initial results are sufficiently interesting to motivate and justify the extension of the analysis in future work. The electrical power generated by wind turbines can be calculated as follows:

$$P=\frac{1}{2}\rho V^3 A_\gamma C_p \eta \tag{A1}$$

where ρ is the air density; V is the wind speed; A_r is the area of the rotor; C_p is the drag coefficient (with a theoretical value of approximately 0.593 and a practical value that reaches 0.45, varying with wind speed and turbine control parameters) and η is the efficiency of the generator set, the transmission, and the mechanical and electrical conversion (ranging from approximately 0.93 to 0.98). The energy released in a certain period (days, months, years) is given as follows:

$$E(t)=\frac{1}{2}\int_0^T \rho(t) A_\gamma C_p \eta V^3(t)dt \tag{A2}$$

where t=time and T=duration or period. In its simplified form, this same equation can be written as

$$E(t)=\frac{1}{2}\overline{\rho} A_\gamma \overline{C}_p \eta \int_0^T V^3(t)dt \tag{A3}$$

where the arguments mean averages.

However, because the wind-speed data are available as monthly averages, the monthly average available energy is given approximately by

$$E(\text{month})=\frac{1}{2}\overline{\rho} A_\gamma \overline{C}_p \eta V_m^3 t_m \tag{A4}$$

where V_m is the average speed and t_m is the period duration (months). This approach neglects the effects of the dispersion of the speeds throughout the month, which could be corrected if the data from the Weibull statistical distribution are available. Even without the Weibull data, it is possible to assess the trend of the complementarity of ANAs between wind power and hydropower in northeast Brazil. To assess the trend of monthly complementarity with the proposed simplifications and approximations, the most important variable is the speed, and by standardizing the unit, other factors are canceled. Therefore, the monthly average energy is proportional to the cube of the speed or

$$E(\text{month}) \propto \overline{V}_m^3 \tag{A5}$$

Over 756 months and for the 10 sets of coordinates, the energy available, E765, will be:

$$E_{756} \propto \sum_{c=1}^{10}\sum_{i=1}^{756} \overline{V}_{ci}^3 \tag{A6}$$

where c=coordinate (1 to 10) and i=month (1 to 756). The complementarity trend was assessed according to the following steps: (a) From the wind-speed data for each coordinate, each value was raised to the cube of the speed. Next, we calculated the average of these values, giving equal weight to each of the ten sets of coordinates in each of the 756 months from January 1948 to December 2010. (b) The availability of monthly natural wind energy normalized as the ratio between the average speed of ten cubes and the average of the monthly average values for all 756 months was estimated. (c) With the database of the ANAh of northeastern Brazil (MWaverage), another normalization was performed to examine the ANAh values and compared with the ANAw values. (d) The normalized ANAh and ANAw values (with an average value per unit of p.u.=1) were obtained. (e) As a result, both hydraulic and wind ENA values are considered above average if they are over 1 and below average if they are less than 1.

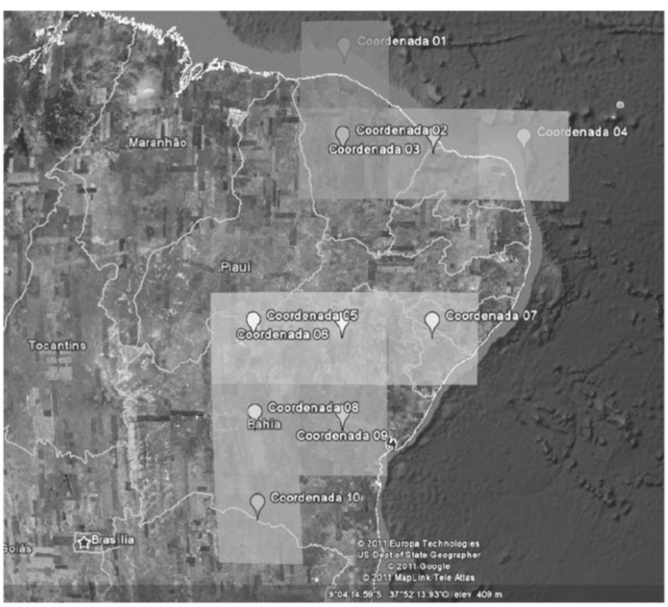

Fig. 16. Wind speed gauge locations in the northeast of Brazil. *Source*: Pinto [8].

Table A.1
Location of the sets of coordinates.

Coordinate	Latitude (°)	Longitude (°)
1	−2.5	320
2	−5	320
3	−5	322.5
4	−5	325
5	−10	317.5
6	−10	320
7	−10	322.5
8	−12.5	317.5
9	−12.5	320
10	−15	317.5

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